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Seismotectonics of the Koyna-Warna Area, India

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Abstract—Reservoir-induced seismicity has been observed near Koyna Dam, India since the early 1960s. In order to understand the seismotectonics of the region we analyzed available seismicity data from 1963 to 1995. Over 300 earthquakes with $M \geq 3.0$ were relocated using revised location parameters (station locations, velocity model, station delays and V_p/V_s ratio). The spatial pattern of earthquakes was integrated with available geological, geophysical, geomorphological data and observations following the M 6.3 earthquake in December 1967, to delineate and identify the geometry of seismogenic structures. From this integration we conclude that the area lying between Koyna and Warna Rivers can be divided into several seismogenic crustal blocks, underlain by a fluid-filled fracture zone. This zone lies between ~6 and 13 km and is the location of the larger events ($M \geq 3.0$). The seismicity is bounded to the west by the Koyna River fault zone (KRFZ) which dips steeply to the west. KRFZ lies along the N–S portion of the Koyna River and extends S10°W for at least 40 km. It was the location of the 1967 Koyna earthquake. The seismicity is bounded to the east by NE–SW trending Patan fault, which extends from Patan on the Koyna River, SW to near Ambole on the Warna River. Patan fault dips ~45° to the NW and was the location of the M 5.4 earthquake in February 1994. The bounding KRFZ and Patan fault are intersected by several NW–SE fractures which extend from near surface to hypocentral depths. They form steep boundaries of the crustal blocks and provide conduits for fluid pressure flow to hypocentral depths. Sharp bends in the Koyna and Warna rivers (6 km south of Koyna Dam and near Sonarli, respectively) are locations of stress build-up and the observed seismicity.

Key words: Reservoir-induced seismicity—case history, seismotectonics, Koyna-Warna earthquakes.

Introduction

The observed seismic activity in the Koyna-Warna area, Maharashtra State, India is unique. It is the only known location in the world where seismicity that began after the start of impoundment of a reservoir (Shivajisagar behind the Koyna Dam), has persisted for more than 30 years. The moderate seismicity has included at least six earthquakes with $M > 5.0$, including the largest, a M 6.3 event that occurred near Koyna at 4:21 a.m. (Indian Standard Time) on December 11, 1967 (22:51 UTC on December 10, 1967). It is also extraordinary because seismicity has been continuously monitored and also because of a number of studies that have been conducted. It is also interesting because until recently we lacked a clear

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understanding of the seismotectonics of this area. In order to understand the seismotectonics we reanalyzed the seismicity data for the period 1963–1995 and integrated it with available complementary lake level, geological, geophysical, geomorphic and neotectonic data. The results of the integration are the subject of this paper. The results suggest that the region between Koyna and Warna consists of several tectonic blocks and the earthquakes occur on the edges of these blocks.

1. Reanalyses of Seismicity Data

Seismicity was first observed in the Koyna area following the start of impoundment of Shivajisagar in 1961. The first seismological observatory to monitor seismic activity in the Koyna region was established in Koyna in 1963. Following the destructive Koyna earthquake of December 10, 1967, a seismological network consisting of seven stations was established during the years 1967 to 1972. A five-station Warna seismic network was established in 1990 to monitor the seismic activity in the neighboring Warna valley, about 35 km south of Koyna. This activity followed the impoundment of the Warna Reservoir. The quality of recording and analysis improved over the years. However, due to various factors the locations obtained by routine analyses (see e.g., Fig. 4.32b in GUPTA, 1992) were inaccurate and inadequate for meaningful tectonic interpretation of the recorded seismicity. The first step in the reanalyses of the seismicity data was to improve the accuracy of the epicentral and (later) hypocentral locations.

To improve the location accuracy the following location parameters, were addressed: (i) location of the seismic stations, (ii) velocity structure, (iii) delay time at a particular station and (iv) ratio of the *P*-wave to *S*-wave velocities (V_p/V_s).

In June 1994 all stations of the Koyna and Warna seismic networks were visited. The station coordinates obtained by using a hand held Global Positioning System (GPS) were compared with the ones in use before. The stations were found to be misplaced by an average of 2 km, with individual mislocations varying from a few meters to over 5 km. The new station coordinates are given in Table 1.

Most of the computer algorithms in use today for locating earthquakes assume a layered seismic velocity model. To choose among the various models that were available, we located a subset of well recorded events with the different models. Based on lower RMS values of travel-time residuals, KAILA's (1983) model (Table 2) was chosen for further analysis (see TALWANI *et al.* (1996) for details).

By iteratively calculating the RMS travel-time residuals for a selected set of earthquakes, the station delays were estimated for stations of the seismic network. These have been incorporated in Table 1. An average V_p/V_s ratio of 1.70 was obtained by plotting Wadati plots (plotting *S*-*P* times against *P*-wave arrival times), for a selected set of 40 well-timed earthquakes recorded in 1993–94.

Table 1

Revised coordinates and station delays for stations of Koyna-Warna seismic network

No.	Station	Station Code	Latitude °N		Longitude °E		Elevation (m)	Station Delay (sec)
			Degrees	Min	Degrees	Min		
1.	Alore	ALO	17°	28.59	73°	38.27	100	−0.07
2.	Chikhali	CKL	17°	14.83	73°	35.17	110	+0.07
3.	Chiplun	CPL	17°	30.96	73°	31.69	75	−0.03
4.	Govalkot	GOV	17°	32.94	73°	29.15	85	
5.	Kolhapur	KOL	16°	42.88	74°	14.53	565	+0.29
6.	Kokrud	KOK	17°	00.45	73°	58.87	555	+0.03
7.	Koyna (Quarry)	KNI	17°	24.50	73°	44.78	640	+0.06
8.	Mahabaleshwar	MAH	17°	55.39	73°	39.71	1360	
9.	Marathwadi	MRT	17°	13.28	73°	56.25	650	+0.09
10.	Pophali	PPL	17°	26.39	73°	40.98	200	
11.	Ratnagiri	RAT	16°	58.98	73°	18.65	40	+0.23
12.	Sakharpa	SKP	16°	59.75	73°	42.80	250	+0.04
13.	Satara	STA	17°	41.31	74°	00.89	650	+0.19
14.	Warnawati	WRN	17°	07.38	73°	53.09	580	+0.02

1A. Relocation of Koyna-Warna Earthquakes

The number of stations and their configuration changed over the years from a four-station network in 1963 to the current eleven stations (Table 1). (Of the 14 stations listed in Table 1, GOV, PPL and MAH are currently inoperative). The accuracy of the time imprinted on the records also improved after 1984–85. Over 90,000 earthquakes have been recorded of which over 1400 had $M \geq 3.0$. Consequently the relocation of the earthquakes, using revised location parameters, was divided into four time periods (Table 3).

Only 64 events were located for the period before the large event on December 10, 1967. These included 17 events with magnitudes between 2.0 and 3.0, Set A in Table 3. These events were located using data from KNI, GOV, STA and MAH stations (Table 1). There were over 54,000 earthquakes between December 10, 1967 and 1982. Of these there were 50 with $M \geq 4.0$. Due to poor absolute times at different stations for most events we used (S-P) times to locate them. The S phase could be clearly distinguished on the distant stations and also on the horizontal component seismographs at various stations. Forty-eight events were located (Set B). Of the nearly 24,000 events recorded between 1983 and 1992, there were 177 with $M \geq 3.0$. Of these there were adequate data to accurately locate 109 events (Set C). Due to the addition of stations in the Warna network and faster recording speed on the MEQ-800 seismographs, earthquakes recorded after 1993 were placed in a different set. Of the 108 events with $M \geq 3.0$, 100 were located (Set D). A complete listing of the hypocentral parameters is given elsewhere (TALWANI *et al.*,

Table 2

P-wave velocity model

V_p km/s	Depth km
4.900	0.0
5.335	1.0
5.765	2.0
5.895	4.0
6.025	6.0
6.155	8.0
6.380	10.0
6.470	13.0
6.560	16.0
6.600	19.0
6.805	25.0
6.895	28.0
6.985	31.0
7.105	34.0
8.100	38.0

KAILA (Pers. Comm., 1983)

Table 3

Recorded and located earthquakes (1963–1995) (Koyna-Warna Region)

Set	Period	Earthquakes Recorded			Earthquakes Located	Quality				Remarks
		Total	$M \geq 3.0$	$M \geq 4.0$	Total	A	B	C	D	
A	1963 to December 10, 1967	1,575	128	7	64	–	–	24	40	Data from three or more stations are available for 64 earthquakes (M 2.0 to 6.3)
B	December 10, 1967 to 1982	54,255	995	50	48	–	1	31	16	Earthquakes with $M \geq 4.0$ were selected for locations; 2 events could not be located due to insufficient data
C	1983 to 1992	23,984	177	9	109	–	6	72	31	Earthquakes of $M \geq 3.0$ were selected for locations; 68 events could not be located due to insufficient data
D	1993 to 1995 (April)	10,311	108	14	100	1	58	40	1	Earthquakes of $M \geq 3.0$ were selected for locations; 8 events could not be located due to insufficient data
	Total	90,125	1,408	80	321	1	65	167	88	

Table 4

List of Koyna-Warna earthquakes with $M \geq 5.0$ and other significant events

Date	HM	Magnitude MERI	Magnitude GUPTA (1992)	Magnitude USGS (m_b)	Magnitude USGS (M_s)
September 13, 1967		5.8*		Foreshock	
December 11, 1967		6.3	6.3		
December 24, 1967		5.0		5.2 Aftershock	
October 29, 1968		5.0			
October 17, 1973		5.1	5.1		
September 2, 1980		4.3		4.9	5.5
September 20, 1980	0728	4.7		4.9	4.3
September 20, 1980	1045	4.9		5.3	4.2
October 4, 1980	1637	4.1		4.5	
February 5, 1983	2253	4.4		4.2	
November 14, 1984	1158	4.4		4.6	
January 6, 1991	2213	4.8		4.4	
August 28, 1993	0426	4.9		4.9	4.5
September 3, 1993	2301	4.7		4.7	
December 8, 1993	0142	5.1		5.0	4.6
February 1, 1994	0930	5.4		5.0	

USGS magnitudes from Preliminary Determination of Epicenters.
* Magnitude of GUHA *et al.* (1970), revised to 5.2 in GUHA *et al.* (1974) and LANGSTON (1981) claims it is $M \leq 4.5$.

1996) and the larger events are listed in Table 4. The epicentral locations with quality D were not considered reliable, and as there were few with quality B or better, to study the spatial pattern of the seismicity we plotted the earthquakes with quality C or better for the various sets. The solution quality ratings, A–D, of the hypocenter indicate the general reliability of the solution. Quality rating A indicates excellent epicenter and a good focal depth; B, good epicenter and fair depth; C, a fair epicenter and poor depth, while D, indicates poor epicenter and depth.

1A.1 Spatial Distribution of Seismicity 1963–1995

Figure 1 shows the location of seismicity for the period between October 1964 and December 1967 (Set A, $M \geq 2.0$ QC). Most of the earthquakes are located north of the east-west segment of Koyna River and near the deepest part of the Shivajisagar (Koyna Reservoir). These earthquakes followed the initial impoundment of the reservoir and their spatial distribution suggests a possible causal association. Set B has been divided into two subsets: December 10, 1967 to 1973 and 1974 to 1982. (There was a M 5.1 event in October 1973). The distributions of $M \geq 4.0$ events occurring in these periods are shown in Figures 2 and 3. The earthquakes occurring between 1967 and 1973 (Fig. 2) are located to the south of the epicentral area of Set A and to the north of Warna River. The epicenters seem to be concentrated in a broad zone to the south of the right angle bend in the Koyna River. The epicenters lying between the Koyna and Warna rivers also suggest a NW-SE trend. This NW-SE trend is also seen in the locations of the aftershocks (solid dots) of the December 1967 event. The $M \geq 4.0$ events between 1974 and 1982 seem to define two areas of activity, an apparent E-W zone just to the south of Koyna River and a broad zone surrounding the Warna River (Fig. 3). The seismicity between 1983 and 1992 ($M \geq 3.0$, QC or better) is very widespread, covering a broad region from the Koyna to the Warna rivers (Fig. 4). The annual distribution shows generally decreasing seismicity from 1983 to 1987 in a broad area south of the Koyna River and extending to the Warna River. The seismicity in the vicinity of the Warna Reservoir appears to be spatially related to the annual filling (impoundment of Warna Reservoir began in 1985). This is particularly noticeable from 1988 onwards. The seismicity in 1992 ($M \geq 3.0$, QC or better), shown in solid dots, appears to be along a NNE-SSW segment which is collinear with the southern part of the Koyna Reservoir and Koyna River before the big bend (Fig. 4). This trend was better defined with subsequent earthquake activity.

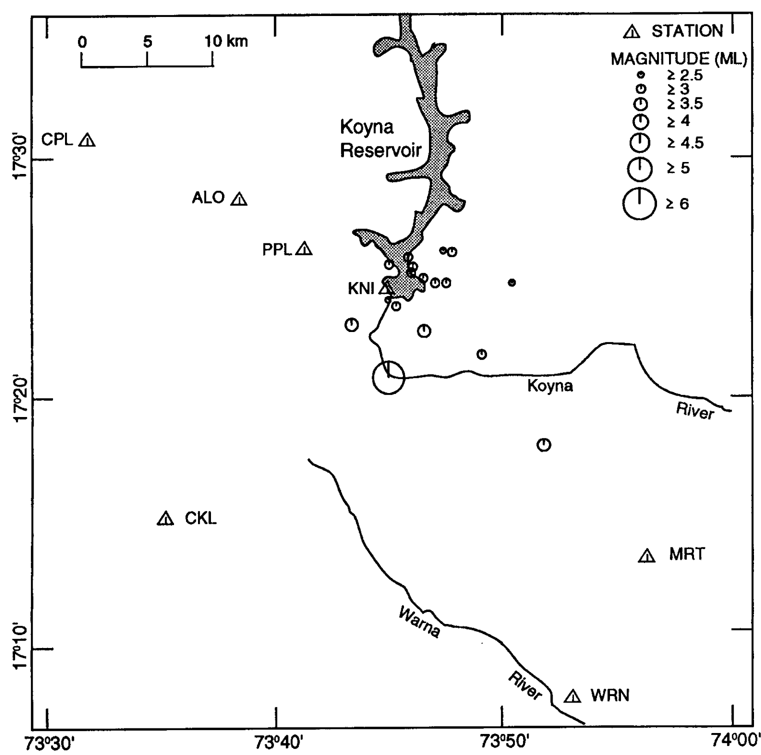

Figure 1
Relocation of earthquakes between 10/1964 and 12/1967.

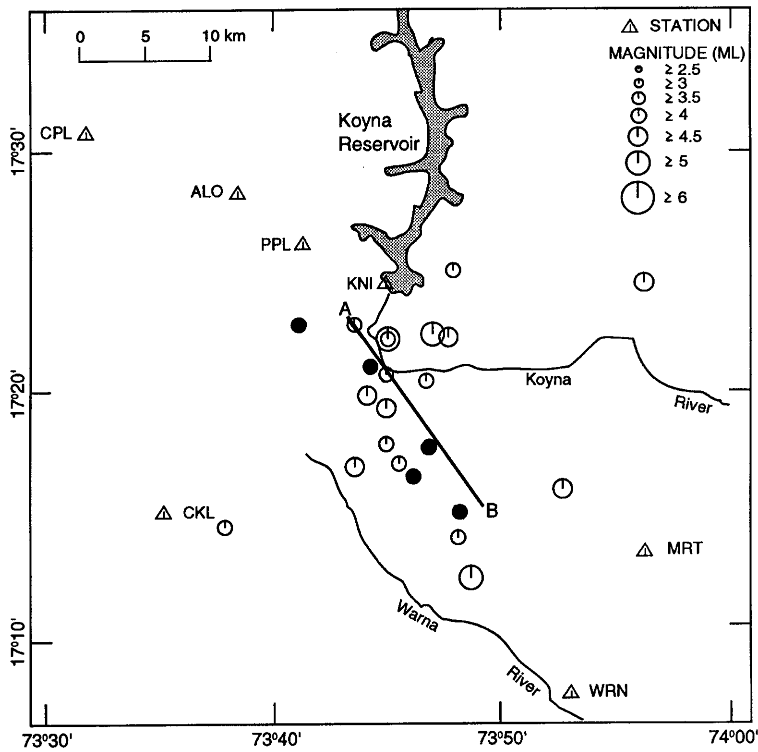

Figure 2
Relocation of earthquakes ($M \geq 4.0$) between December 10, 1967 and 1973. Aftershocks of the December, 1967 main shock are shown by solid symbols, they lie along a NW–SE trend AB, defined by the aftershocks of the February, 1994 event (Fig. 9).

The seismicity in the period 1993—April 1995 (Fig. 5) defines two clusters: A dense one near the upper reaches of Warna Reservoir and a smaller one south of the right angle bend in the Koyna River. The February 1, 1994, M 5.4 Koyna earthquake was located in the northern cluster. The annual distribution of seismicity shows that most of the seismicity was concentrated near Warna Reservoir in 1993. The pattern continued in 1994–95. In 1995 we notice that Warna seismicity had migrated to the west and northwest of intense clusters at the confluence of Bhogiv *nala* and Warna River. The outward migration of epicenters is characteristic of reservoir-induced earthquakes, suggesting that the observed seismicity in the vicinity of the Warna River is associated with the annual impoundment of Warna Reservoir.

1A2. Detailed Analysis of Seismicity for the Period 1993–1995

For the period starting with 1993 and through April 1995, 100 events with $M \geq 3.0$ were located; of these, 58 were located with a quality factor B and one with an A. It was decided to analyze this set of 59 events further to obtain the depth distribution. To check the reliability of the depths obtained for the 59 events, each event was further analyzed for the stability of the calculated depths. For each event the RMS error was calculated for the locations determined by using fixed depths (in the location program) varying from 1 to 20 km. The depths were also calculated for different starting depths. Figure 6 shows the plots for two events on January 03, 1994 at 08:57 and July 16, 1993 at 06:24. The calculated depths of these events, 11.2 km and 8.8 km agree well with the depth corresponding to the lowest RMS value (in the fixed depth vs. RMS plot). They also agree well with depth estimates obtained from various starting depths.

Of the 59 events that were chosen for the depth analysis 40 gave reliable depths. The locations of these earthquakes are shown in Figure 7. Similar to the location of the larger set of events for this period, their locations define two clusters, one near the bend of the Koyna River and the other near the confluence of Bhogiv *nala* and Warna River. The depth distribution of these events (Fig. 8) demonstrates that the earthquakes lies between the depths of 5 and 16 km with 80% of them lying between 7 and 13 km.

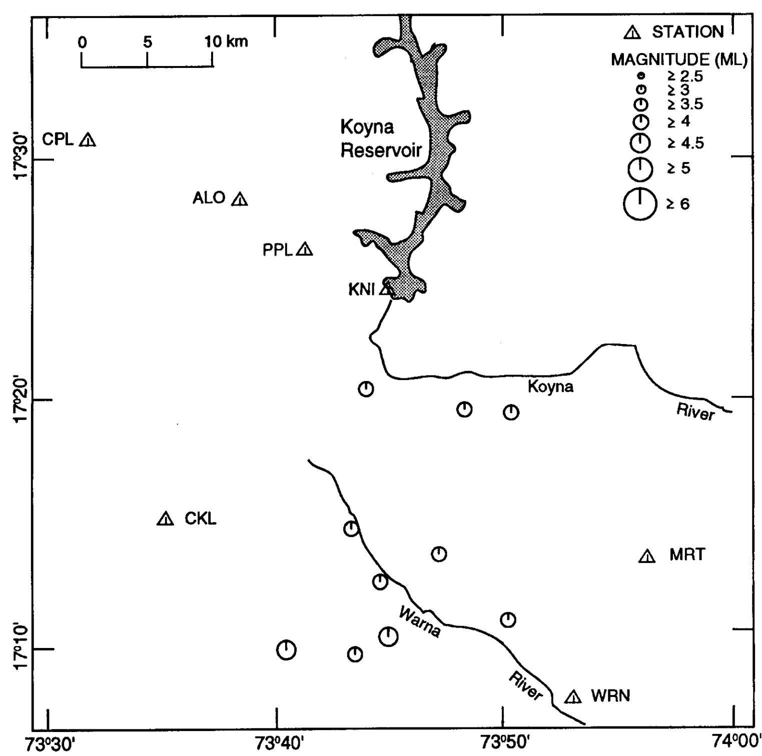

Figure 3
Relocation of earthquakes ($M \geq 4.0$) between 1974 and 1982.

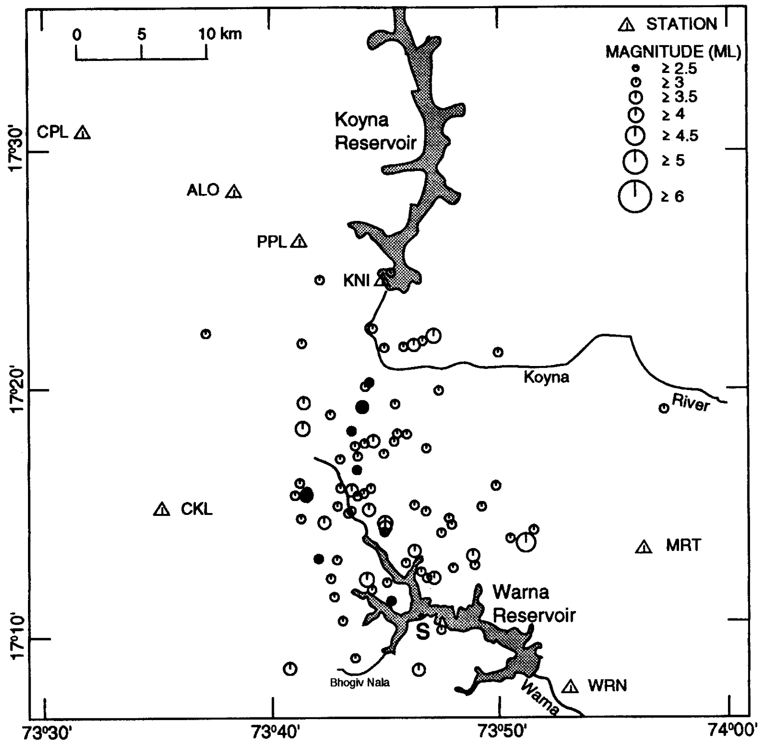

Figure 4
Relocation of earthquakes ($M \geq 3.0$) between 1983 and 1992. The earthquakes in 1992 (solid symbols) define a NNE–SSW trend, identified as the Koyna River Fault Zone.

The results of the detailed analyses revealed that most of the earthquakes south of Koyna River and the northwestern most of the Warna earthquakes lie in a narrow NNE–SSW trending "channel" lying between about 6 and 14 km depths, on a fault plane with a steep (possible SE) dip. No obvious fault plane was defined by the hypocentral distribution of the second cluster located at the confluence of the Bhogiv *nala* and Warna River.

1A.3 Detailed Analysis of Aftershocks of the February 1, 1994 Earthquake

The magnitude 5.4 earthquake that occurred on February 1, 1994 was the largest event since the 1967 main shock. It was followed by 79 aftershocks with $M > 1.0$ in the next 24 hours covering ~ 250 km area. The aftershock locations varied in quality. To seek possible structures associated with the aftershocks we chose the better located events (QC or better, $\text{RMS} \leq 0.25$ sec and $\text{ERZ} < 5.0$). ERZ is a measure of the error in the hypocentral depth calculations. This subset of 28 events defines three linear features (Fig. 9), two parallel features trending NW–SE terminating in a NE–SW trend. Stereo plot view of these earthquakes from the southeast and southwest show that the two sets of NW–SE trending hypocenters define the NE and SW boundaries of NW–SE trending blocks. The NE–SW trending hypocenters define the southeast boundary of the block. A NW–SE cross section through the main shock and adjacent NW–SE trending hypocenters (within 2 km of the line AB in Fig. 9) defines two parallel planes dipping to the NW at about 43° (Fig. 10). The two parallel planes (defined by the aftershocks) lie above and below the main shock. The fault plane solution for this event (Fig. 9) suggests normal faulting on a NE–SW plane dipping 45° to the northwest or southeast. The distribution of the hypocenters of the aftershocks suggests that the fault plane dips to the northwest.

Thus the hypocentral locations of (the better located) aftershocks of the February 1, 1994 earthquake define a block dipping northwest bounded to the northeast and southwest. The hypocenters lie in two roughly parallel northwest dipping planes, which (probably) define the top and bottom of the block. The hypocentral locations define the boundaries of the block which are faulted and fractured and provide conduits for fluid flow.

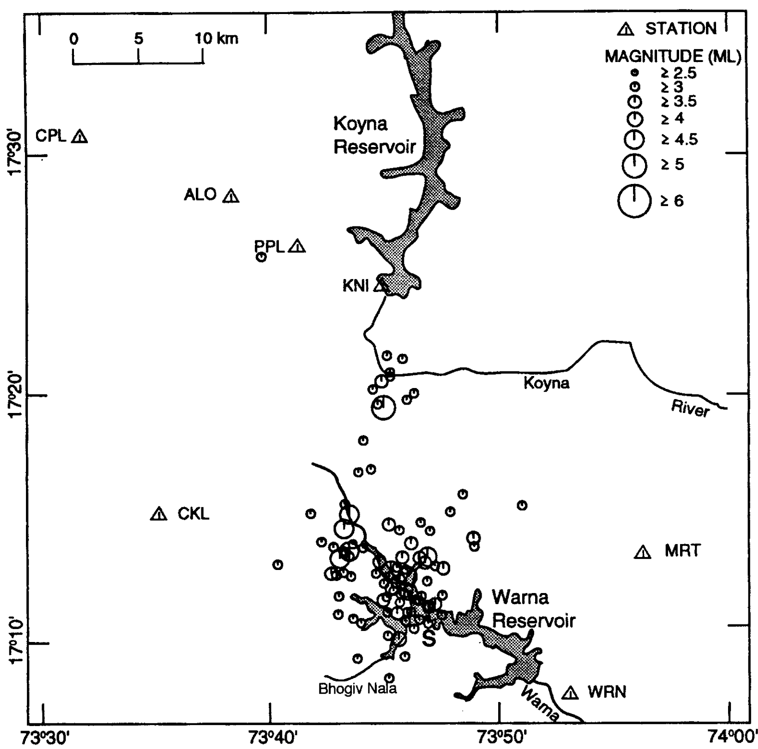

Figure 5

Relocation of earthquakes $M \geq 3.0$ earthquakes between 1993 and April, 1995. Increased seismicity near Warna River followed the impoundment of the Warna Dam. *S* shows the location of Sonarli.

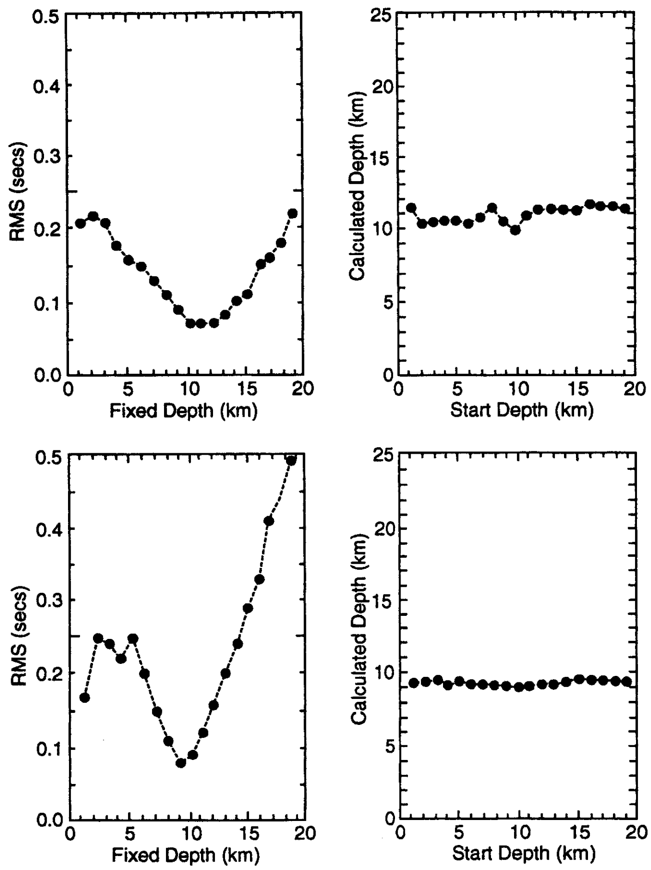

Figure 6
Depath analyses of two events on January 3, 1994 (top) and July 16, 1993 (bottom).

1B. Fault Plane Solutions

Various data suggest that there is more than one fault plane associated with the observed seismicity. Available fault plane solutions were reviewed and new ones obtained for well recorded recent earthquakes.

1B.1 Fault Plane Solutions of December 10, 1967 Main Shock

Several workers have obtained fault plane solutions for the 1967 main shock. The results have been summarized in Table 5, and the methods used to obtain the fault plane solutions are summarized in Table 6. Except for an early solution by GUPTA *et al.* (1969), all solutions suggest left lateral strike-slip faulting (Fig. 11). More recently GUPTA (1992) has suggested his preference for the left-lateral strike-slip solution. The strike of the fault plane obtained by various workers using different techniques is within about $\pm 10°$ of N20°E–S20°W. (Khattri's solution is

Table 5

Source Mechanisms for the Main Shock
(December 10, 1967 at 22 h 51 m UTC)
Location 17° 20.8′N, 73° 44.88′E, 10.4 km deep

Fault Planes I			Fault Planes II				
Strike°	Dip°	Rake°*	Strike°	Dip°	Rake°	Fault Type	Author
206	66NW	165	110	74SW	24	Strike-slip	Tandon and Chaudhury, 1968
328	90	−90				Normal	Gupta *et al.*, 1969
217	72NW	176	126	84SW	18	Strike-slip	Lee and Raleigh, 1969
170	80W	160	76	70SSE	11	Strike-slip	Khattri, 1970
201	75NW	0	111	90	15	Strike-slip	Sykes, 1970
203	70NW					Strike-slip	Tsai and Aki, 1971
202	80NW	177	112	88N	10	Strike-slip	Bangar, 1972
190	78NW	−5°	111	85N	−12	Strike-slip with small normal component	Singh *et al.*, 1975
16	67E	−29	117	64	205	Strike-slip with small normal component	Langston, 1976
a.206	78NW	0	116	90	12	Strike-slip	Chandra, 1977
b.206	51NW	−20	129	75NE	−40	Strike-slip	

* Rake angle measured (in the fault plane) counterclockwise from strike direction.

Table 6

Method used to obtain fault plane solution for the main shock

Method/Data	Remarks	Author
P-wave first motion data	From 89 stations in India and outside	Tandon and Chaudhury (1968)
P-wave first motion data	From WWSSN and Indian stations	Gupta *et al*. (1969)
P-wave first motion data	From 26 WWSSN, 17 Indian, 24 ISC, 18 USCGS and 1 Canadian stations	Lee and Raleigh (1969)
P-wave fist motion data		Khattri (1970)
P-wave first motion and *S*-wave polarization data	WWSSN stations	Sykes (1970)
Analysis of Rayleigh and Love wave data	6WWSSN stations. Also obtained $M_o = 1.8 \times 10^{26}$ dyne-cm	Tsai and Aki (1971)
P, PKP first motions and polarization or *S*-wave first motion data	WWSSN and Indian stations	Bangar (1972)
Analysis of Rayleigh waves recorded on long-period vertical component seismograms	30WWSSN stations	Singh *et al*. (1975)
Inversion of long-period body wave (*P*, *pP*, *sP*)	17WWSSN stations	Langston (1976)
P-wave first motion data	WWSSN stations	Chandra (1977)

N10°W–S10°E). The fault was found to have a steep northwesterly dip (66°–80°) by most workers, however LANGSTON (1976) obtained an easterly dip. Most workers obtained pure strike-slip to a small reverse component along with the strike-slip motion, however SINGH *et al.* (1975) and LANGSTON (1976) obtained a small normal faulting component. LANGSTON's (1976) solution differed from other solutions, in that he suggested an easterly dipping fault. He used a generalized inverse method to analyze the first 25 s of the long-period P and SH wave forms recorded by the WWSSN. He inferred a shallow source, 4.5 ± 1.5 km, and suggested that such a shallow source would be associated with a complex source time function. As a result, the interference of P, pP and sP made apparent compressional P-wave polarities where the direct P wave was really dilatational. Thus taken together, the various fault plane solutions support left-lateral strike-slip faulting or a fault oriented from about N10°E–N20°E. This result is in general agreement with the conclusions of many recent studies (see e.g., GUPTA, 1992). LANGSTON's (1976) solution suggests a southeasterly dip, whereas other studies suggest a northwesterly dip. We will discuss the direction of the dip when comparing with other data.

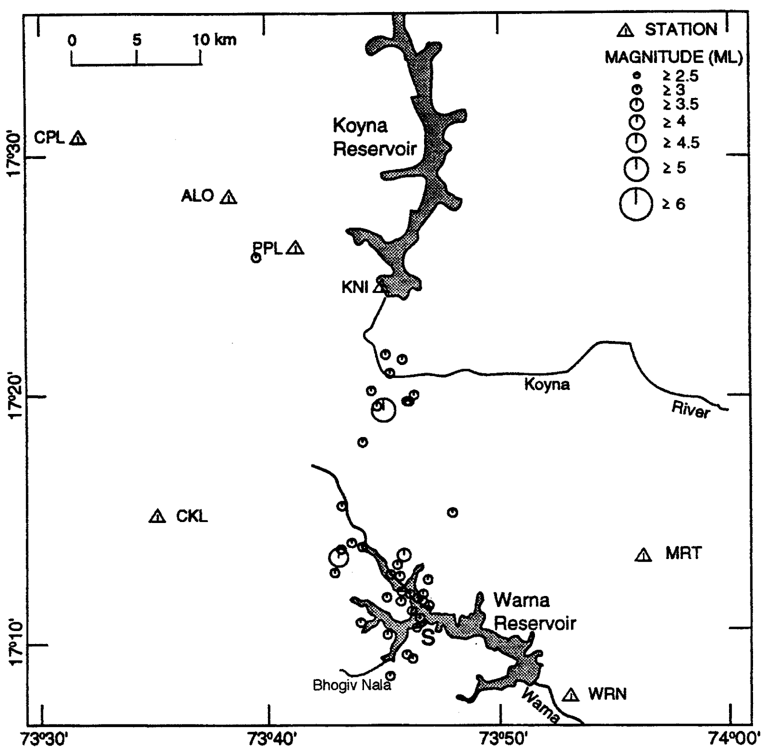

Figure 7
Earthquakes in 1993–1995 with best depth control. S shows location of Sonarli.

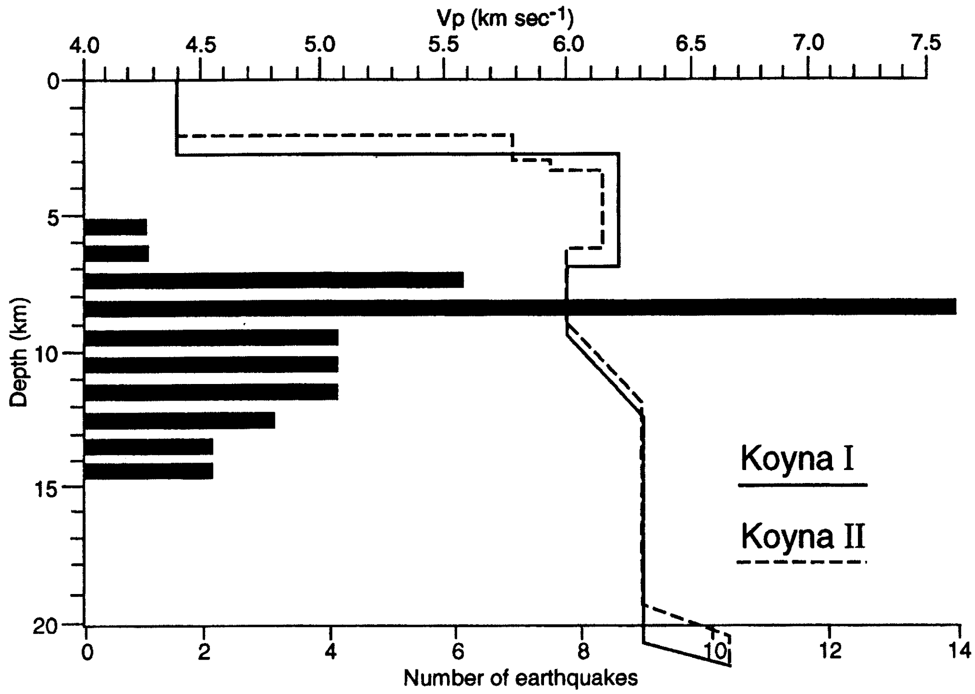

Figure 8
The depths of earthquakes compared with the velocity models by KRISHNA *et al.* (1983). Note how most of the seismicity lies in the low velocity zone.

Source properties for the main shock consist of estimates for the seismic moment (M_o), source dimensions, stress drop ($\Delta\sigma$) and displacement (u). The results of various studies have been summarized in Table 7. Estimates for M_o range between ~ 1 to 78×10^{25} dyne-cm (10^7 dyne-cm $= 1$ Nm). Estimates based on careful body and surface wave modeling are generally consistent and range between 3 and 18×10^{25} dyne-cm, whereas the value obtained by KHATTRI *et al.* (1977), based on a spectral analysis of teleseismic body waves, is anomalously high and probably overestimates the true M_o. The displacement spectra of strong ground motion seismograms resulted in a small source dimensions (2.5 km) and large stress drop (238 bars) (23.8 MPa). Other estimates ranged between 18 and 40 km for source dimension and 6 to 47 bars (0.6 to 47 MPa) stress drop.

1B.2 Fault Plane Solutions of Foreshocks and Aftershocks of December 10, 1967 Earthquake

LANGSTON (1981) and RAO *et al.* (1975) and LANSTON and FRANCO-SPERA (1985) obtained fault plane solutions for a foreshock and aftershocks of the December 10, 1967 Koyna earthquake. For the foreshocks, which occurred on

Table 7

Source properties of the main shock

$M_o \times 10^{25}$ dyne-cm	Source dimension km	$\Delta\sigma$ bars	u cm	Method	Author
18				Surface waves analysis	TSAI and AKI (1971)
8.2	23–40	6.2–19.8	108	Spectral analysis of Rayleigh waves	SINGH *et al.* (1975)
77.6	17.9 ± 1.2 to 22.5 ± 5.8	47		Spectral analyses of teleseismic body waves	KHATTRI *et al.* (1977)
3.2 ± 1.4				Inversion modeling of body waves	LANGSTON (1976)
0.86	2.5	238	126.8	Displacement spectra from strong motion accelerograph records	GUPTA and RAM BABU (1993)

September 13, 1967, GUHA *et al.* (1970), had assigned magnitudes of 5.8, 4.5 and 4.5. LANGSTON (1981) examined the WWSSN records for the stations POO and NDI and argued that the magnitudes were closer to 4.0–4.5. A left-lateral strike-slip fault plane solution was obtained for the larger event (Table 8). A left-lateral strike-slip solution also was obtained for the M 5.0 aftershock on December 12, 1967 at 15h 48m by RAO *et al.* (1975). For a M 5.3 aftershock, which occurred at 0600h 18m on December 12, 1967, LANGSTON and FRANCO-SPERA (1985) obtained a normal faulting solution on a NW–SE trending fault (Table 8). A similar solution was obtained for a m_b 5.3 earthquake on September 20, 1980, using a moment tensor solution (DZIEWONSKI *et al.*, 1988). These fault plane solutions are shown in Figure 12.

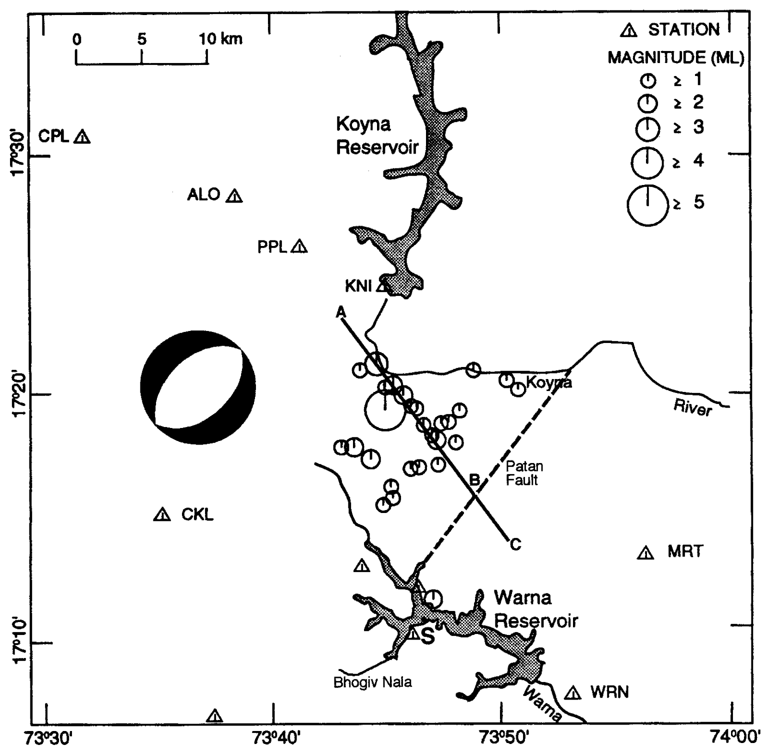

Figure 9
Location of subset of aftershocks of February 1, 1994 event that occurred within 24 hours. Only events with RMS ≤ 0.25 s or better have been plotted. The fault plane solution for main shock (TALWANI, 1994) shows normal faulting on a NW–SE trending fault. AB is inferred to be a NW–SE trending block boundary. B lies on the Patan fault inferred from trends of rivers (PATWARDHAN *et al.*, 1995). A vertical cross section along the line AC is shown in Figure 10.

Table 8

A. Fault plane solutions of a foreshock and aftershocks, B. Moment Tensor Solution of m_b 5.3 earthquake on September 20, 1980

Date: Day / Origin Time: hour	Date: Month / Origin Time: min	Date: Year / Origin Time: sec	Magnitude	Fault Planes I: Strike°	Fault Planes I: Dip°	Fault Planes I: Rake°	Fault Planes II: Strike°	Fault Planes II: Dip°	Fault Planes II: Rake°	Fault Type	Author
A.											
13	9	1967	5.8 (Guha)	20 ± 5	90 ± 15	0 ± 35				Strike-Slip	Langston (1981)
6	23	31	4.0–4.5								
12	12	1967	5.3	100 ± 20	40 ± 10	240 ± 20				Normal	Langston and Franco-Spera (1985)
06	18	37									
12	12	1967	5.0	22	56	187	116	82	−35	Strike-slip	Rao *et al.* (1975)
15	48	55									
B.											
20	9	1980	5.3	139	29	−111	342	63	−79	Normal	Dziewonski *et al.* (1988)
10	45	29									

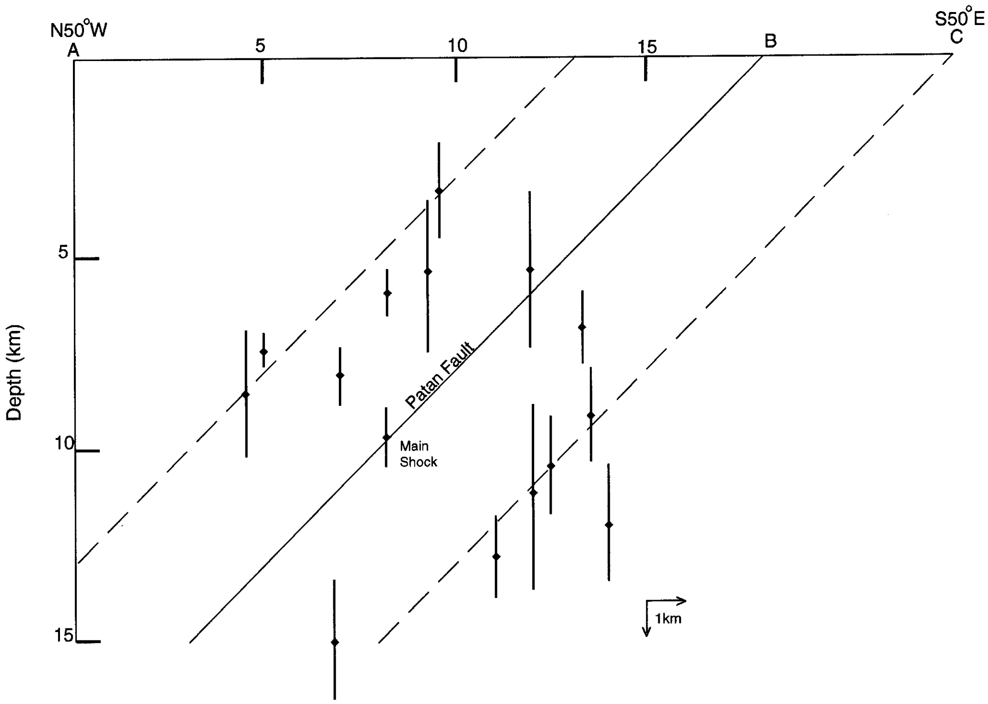

Figure 10
A NW–SE cross section showing earthquakes along AC in Figure 9. Only earthquakes lying within 2 km of AB have been plotted. The dip of the Patan fault, passing through the main shock, has been inferred from the fault plane solution. Its surface projection outcrops near the fault location inferred from changes in river course (B) by PATWARDHAN *et al.* (1995). Dashes lines have been drawn parallel to the dip of the Patan fault.

1B.3 Composite Fault Plane Solutions

RASTOGI and TALWANI (1980) relocated about 300 events occurring between 1967 and 1973. Based on the spatial distribution of the events, they identified three trends of epicenters and obtained composite fault plane solutions (CFPS) for them (Table 9). Two solutions suggested left-lateral strike-slip faulting on NE–SW planes with a dip of 80° to SE for one solution and 80° to NW for the other. The third solution suggested normal faulting on a NW–SE plane. GUPTA *et al.* (1980) obtained CFPS for eight events with $M \geq 4.0$. They used a combination of foreshocks and aftershock data to obtain the CFPS. For the eight events, they obtained strike-slip solutions for two events on roughly north-south striking planes. They obtained normal faulting for five events on generally NW–SE striking fault planes and reverse faulting for one event on a NE–SW striking fault plane (Table 9).

Table 9

Composite fault plane solutions

Date D	Date M	Date Y;	H:M	Fault Planes I Strike°	Fault Planes I Dip°	Fault Planes I Rake°	Fault Planes II Strike°	Fault Planes II Dip°	Fault Planes II Rake°	Fault type	Author
1967–1973											
NW trending zone				328	40	−98	318	50	−97	Normal	Rastogi and Talwani (1980)
NNE zone near dam				35	80	159	301	70	11	Strike-slip	Rastogi and Talwani (1980)
NNE zone W of dam				23	80	10	112	80	10	Strike-slip	Rastogi and Talwani (1980)
17	10	1973; (4FS + 8AS)*	15:24	5	76	−175	97	86	−15	Strike-slip	Gupta *et al.*(1980)
17	02	1974; (1FS + 2AS)	14:06	346	80	−90	166	10	−90	Normal	Gupta *et al.* (1980)
28	08	1974; (2AS)	20:20	358	80	−90	178	10	−90	Normal	Gupta *et al.* (1980)
11	11	1974; (1FS + 1AS)	15:11	316	40	−90	136	50	−90	Normal	Gupta *et al.* (1980)
20	12	1974; (1FS)	14:16	32	74	90	212	14	90	Reverse	Gupta *et al.* (1980)
2	12	1975;	07:40	318	60	−90[1]	138	30	−90	Normal	Gupta *et al.* (1980)
		(1AS)		298	22	−90[2]	118	28	−90	Normal	Gupta *et al.* (1980)
24	12	1975;	13:25	258	30	−90[1]	78	60	−90	Normal	Gupta *et al.* (1980)
		(2FS + 14AS)		293	70	−90[2]	112	20	−90	Normal	Gupta *et al.* (1980)
14	03	1976;	05:16	350	62	−156[1]	91	70	−31	Strike-slip	Gupta *et al.* (1980)
		(6AS)		2	10	−170[2]	81	88	−100	Strike-slip w/normal comp.	Gupta *et al.* (1980)

* FS and AS are foreshocks and aftershocks.
[1,2] are two possible solutions for the earthquake.

1B.4 Fault Plane Solutions of Eight Events in 1993–1994

We obtained fault plane solutions for eight events with magnitudes between 3.7 and 5.4 that had been well recorded on stations of Koyna and Warna seismic networks (Fig. 13). Seven of the eight earthquakes are located near Warna and the eighth was the *M* 5.4 Koyna earthquake of February 1, 1994. Multiple solutions were obtained for some events because of a lack of constraints. The results are summarized in Table 10.

The *M* 5.4 event was associated with normal faulting. Of the seven Warna events, two each were associated with strike-slip and reverse faults and the remaining were associated with normal faults. The orientation of fault planes varied greatly.

1B.5 Discussion

The various fault plane solutions suggest that the prominent style of faulting is by left-lateral strike-slip motion on N–S to NNE–SSW striking faults. Normal faulting occurred on NW–SE to E–W striking faults and in some cases on NE–SW striking faults (especially for earthquakes occurring near Warna).

Langston and Franco-Spera (1985) obtained a normal fault mechanism with a strike of 100° ± 20° and a dip of 40° ± 10° and rake, 240° ± 20° for a m_b 5.3

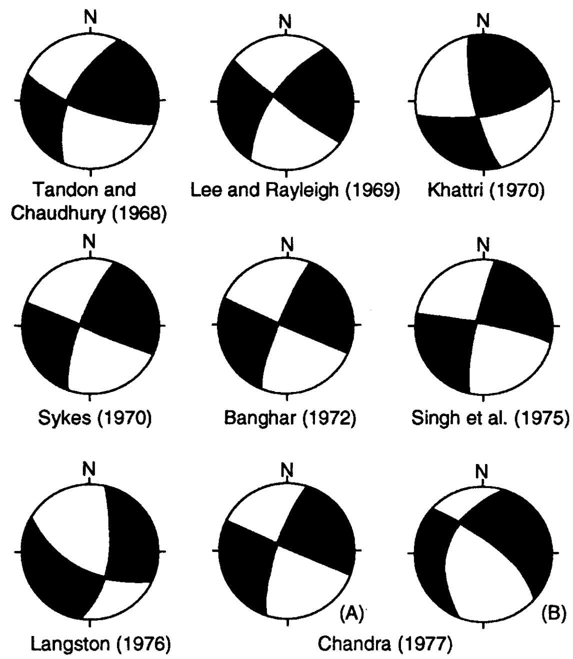

Figure 11
Various fault plane solutions for the Koyna December 10, 1967 main shock.

Table 10

Fault plane solutions for 1993–94 events

	Date				Fault Planes I			Fault Planes II				
No.	D	M Origin Time H:M	Y	Magnitude	Strike°	Dip°	Rake°	Strike°	Dip°	Rake°	Fault Type	Author
1	28	08	93	4.9	165	40	−180	75	90	50		This study
		04:26			319	88	86	250	5	20		
2	03	09	93	4.7	296	90	−25	25	25	−180	Strike-slip	This study
		23:01										
4	22	10	93	4.3	16	37	−25	135	70	−120	Strike-slip/normal	This study
		01:14										
5	08	12	93	5.1	54	32	−107	35	60	−100	Normal	This study
		01:42										
					44	45	−49	173	58	−123	Normal	DZIEWONSKI *et al.* (1994)
6	21	12	93	4.0	02	50	−160	260	75	−40	Normal/strike-slip	This study
		10:15									Not well constrained	
7	22	01	94	3.8	319	56	135	75	65	50	Strike-slip w/reverse	This study
		11:12									component	
8	01	02	94	5.4	45	35	−130	91	64	−105	Normal	This study
		09:30			50	45	−90	50	45	−90	Normal	TALWANI (1994)
9	01	03	94	3.7	325	65	160	63	72	27	Strike-slip w/reverse	This study
		16:07			302	56	68	85	40	120	component	
					320	50	−130	12	50	−60	w/normal	
											component	

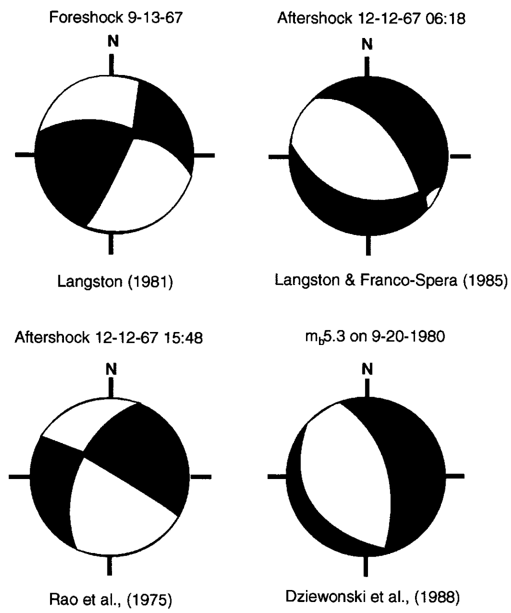

Figure 12
Fault plane solutions of the foreshock and aftershocks of the December 10, 1967 Koyna earthquake. The fault plane solution of the September 1980 event is also shown.

aftershock of the December 10, 1967 event. The aftershock which occurred on December 12, 1967 at 06:18 UTC could not be located. However, the locations of six aftershocks with $M \geq 4.0$ that occurred from December 1967 to February 1968 (Fig. 2) also define a NW–SE fault zone. Although the locations of these events exhibit some scatter, they delineate a NW–SE zone. Interestingly this zone is almost exactly along the NW-SE trending boundary of a block defined by the aftershocks of the February 1, 1994 earthquake (Fig. 9).

The orientations of the fault plane solutions obtained by different authors will be used to infer the orientations and boundaries of various blocks delineated by the seismicity, geology and geomorphological features (next section).

2 Geology and Tectonics of the Area

To understand the seismotectonics of a region we compared the seismicity data with complementary data. These data consist of observations immediately following the 1967 earthquake, geomorphological and satellite imagery data and geological and geophysical observations. The various data were integrated to describe the tectonic framework.

2A. Observations Following the 1967 Koyna Earthquake

Very detailed investigations were carried out following the 1967 main shock by the officers of the Geological Survey of India (GIS Report, 1968). These observations described ground deformation, incidences of water level changes and general felt reports and perceived directions of felt ground motion. Widespread surface deformation was observed in the meizoseismal area (GSI Report, 1968; SATHE *et al.*, 1968). These are located in Figure 14. Slumping or rock slips (GSI Report, 1968) was observed in areas of high relief, hillsides and was parallel to the surface contours. The rock slips were rarely deep and were mainly due to weathered and open jointed columns of basalt coming down with the loose slope wash (GSI Report, 1968). At other locations the earthquake caused the development of ground fissures (mole cracks commonly observed in areas of strike-slip faulting). Although

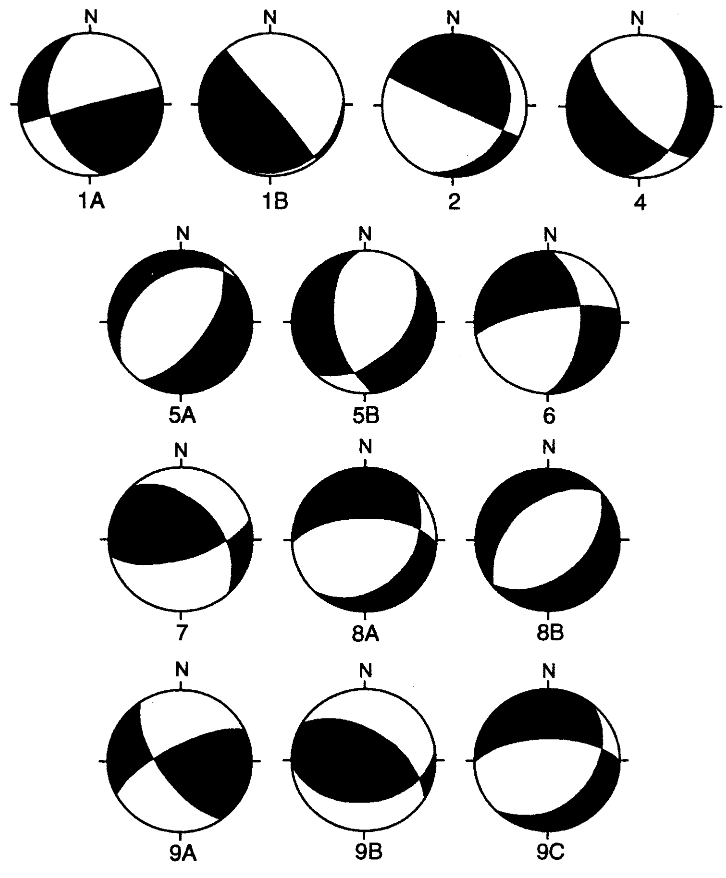

Figure 13
Fault plane solutions of selected events in 1993–94. See also Table 10.

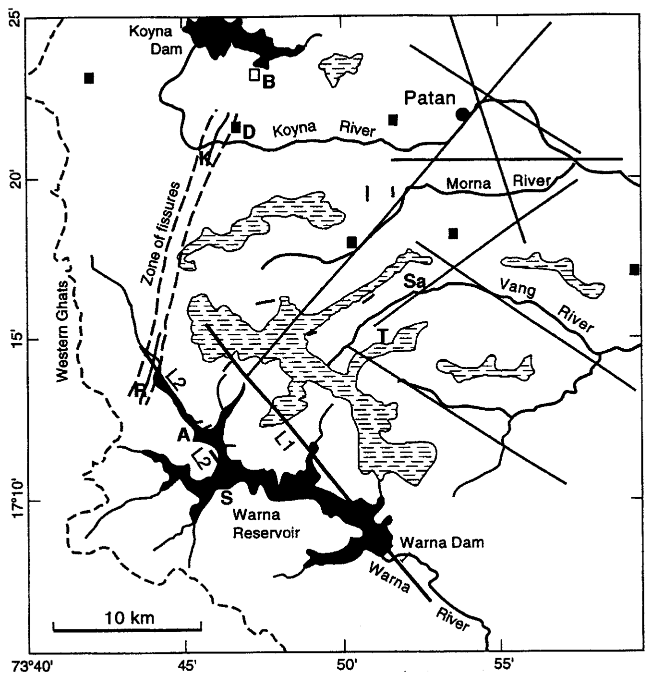

Figure 14
Location of fissures and slumps (short dashes) associated with the main shock. The hatched pattern shows areas with elevation exceeding 1000 m. Location of wells is shown where water levels went up [solid squares] and went down [open squares]. Map also shows escarpment trends along the continental divide (dashed). The solid lines show faults interpreted from changes in the course of the Koyna River and its tributaries by PATWARDHAN *et al.* (1995). The zone of fissures associated with the 1967 earthquakes extends from near Baje (B) to Randhiv (R) via Donichawadi (D) and Kadoli (K). Sonarli (S) lies at the confluence of the Bhogiv *nala* and the Warna River. A, Sa and T show the locations of Ambole, Salve and Tamine, respectively. The lineaments L_1 and L_2 are from LANDSAT in INSAT images.

such fissures and cracks were observed at many locations, the regular pattern and continuity of cracks was discernible in weathered traps and soil only between Nanel and Kadoli near Donichiwada Village, 5 km southwest of the dam. The main fissures trended N10°W–N25°E and the diagonal tension cracks trended N10°W–N40°W. According to the GSI Reort (1968), about 12 km southwest of Kadoli Village, small fissures and cracks are seen on the lower contours of the western ridge face of Rundhiv Village trending N20°E. These extend over 50 m and have a depth ≤ 1.8 m. These fissures were along the same alignment as those near Donichiwada.

"*Detailed examination of the hill slopes of the intervening area between Kadoli and Rundhiv did not reveal the continuity of the features*" (GSI Report, 1968). However, SATHE *et al.* (1968) suggest that the "*... zone of fissures near Donichiwada* (*which includes Baje*, *Nanel*, *Kadoli*) ... *extend up to Rundhiv*". N–S trending *en-echelon* fissures were also observed near Morgiri, located about 10 km east of Kadoli, although they were not as well developed as at Kadoli (SATHE *et al*., 1968). These authors further suggest that the NNE–SSW fissures observed near Kadoli were associated with the fault causing the December 1967 earthquake.

Changes in water levels were observed in streams and in wells over a widespread area. In most of the wells the rise in water levels varied between about 5 and 30 cm. In some streams up to 1.7 m rise in water level was reported. At three locations the water level decreased. Of the 23 locations for which we have reports of changes in water level, seven are located in the vicinity of the epicentral region of the observed seismicity. Two of these locations show an interesting pattern. The water level rose at Donichiwada and declined at Baje (Fig. 14). These two places are located on either side of the inferred fault based on ground fissures. In addition to changes in water levels, the water turned milky and turbid at several locations, providing evidence that the earthquake caused widespread changes in the ground water flow pattern.

The report by the GEOLOGICAL SURVEY of INDIA (1968) provided excellent details of the felt effects of the earthquake. Many of the reports described the perceived direction of motion at a particular location (see TALWANI *et al*., 1996 for details). These observations are consistent with strike-slip faulting on a N10–15°E–S10–15°W trending fault.

2B. Geomorphological Observations

2B.1 Trend of the Koyna River

SAHASRABUDHE *et al*. (1971) mapped the geology of the area and also noted that the trends of the escarpment along the continental divide and the Koyna River 6 km to its east were similar. They noted that "... *the en-echelon displacement pattern of the hill trends and similar changes in the Koyna River courses can be made out in topographic sheets*". They noted that joints and shears were responsible for the topography and have, to a major extent, controlled the drainage pattern in the area. They concluded that shearing had been responsible for the *en-echelon* pattern of the ridges and the similar disposition of the Koyna valley.

Later authors, e.g., GUPTA *et al*. (1980), have suggested that the right angle bend in the Koyna River is fault controlled, whereas GUPTE (1968) attributes the bend to river capture.

2B.2 Evidence of Neotectonics

Reconnaissance geologic mapping and aerial reconnaissance near the Koyna Dam by HARPSTER *et al*. (1979) showed that the fissures that developed during the December 1967 event were the result of displacement on a pre-existing fault zone.

They named it the Donichiwada fault zone with an overall strike of N35°E. They noted that there were retaining walls that were offset as much as 1 m left-laterally and the presence of clay within the fault zone indicated that the Donichiwada fault was active.

2B.3 Interpretation of Aerial Photographs in the Koyna Region

DESHPANDE and JAGTAP (1971) described the main features in aerial photographs of the area taken from a height of 19,500 ft. The most prominent feature was the prominent steep, north-south fractures. The north-south fractures were found to be planar, systematically oriented and cross-cutting. Continuous individual or zones of fractures cut the cliffs, laterite caps and particularly, excavation flows (SNOW, 1982).

2B.4 Matching Erosional Surfaces

In order to seek geomorphic evidence of uplift, SNOW (1982) compared erosional surfaces on either side of the N–S section of the Koyna River using Survey of India topographic maps. On one profile, he noted displacement of the two oldest surfaces near Koyna Reservoir, indicating down faulting to the west. Thus the geomorphic evaluation of the E–W erosional surfaces indicates the presence of a N–S trending fault with the west side down thrown.

2B.5 Geomorphic Investigations Near Patan

PATWARDHAN *et al.* (1995) studied geomorphic features, especially the courses of the rivers Kera, Morna and Vang, the three major tributaries of Koyna in the Patan Taluka (a subdivision of a tax district, covering several villages). The town of Patan is located about 16 km SSE of Koyna Dam. They noted that "... *the course of Koyna is almost linear, parallel to the western ghats right from the hills of Mahableshwar up to the present establishment of Koyna Nagar town and Helwak* (*Fig.* 14). *The river takes a sudden turn eastward and flows again in a linear valley up to Patan, where it is joined by the Kera which also takes a NNW–SSE course* (*roughly*) *parallel to the initial course of Koyna.* ***Just before Patan, the Koyna also takes a sudden northeasterly course*** *(emphasis added) and beyond Patan after flowing eastward for a short distance, it takes a linear southeasterly course right up to Karad where it joins the Krishna. Almost parallel to the course of the Koyna flow the tributaries Morna and Vang. The southeasterly course of the Koyna from Patan to Karad and a similar course of Varna* (*Warna*) *on which the Chandoli dam has been constructed are remarkably linear*".

PATWARDHAN *et al.* (1995) further suggest that these geomorphological features (changing trends in the course of the rivers) "may be consequent to movements in deep seated faults with the pre-Trap formations ...". The reactivated basement faults are expected to follow major foliation directions and planes of weakness of the metamorphosed basement rocks. They further suggest that "the shear pattern observed in the thin Deccan basalt cover largely follows the movement directions of faults within the basement and has, in turn, controlled the linear courses of the rivers as well as facilitated the deep erosion by them. They infer several NE–SW, E–W and NW–SE trending faults or shear planes (Fig. 14). These directions agree well with those observed on a LANDSAT image by LANGSTON (1981).

One of the inferred faults trending N45°E–S45°W, based on the north-easterly courses of the Koyna River near Patan and Morna River near Morgiri, if extended further southwest is collinear with a NE–SW trending tributary of the Warna River located between the Ambole and Atoli. We infer this fault, herein named the Patan fault, to be a block boundary and will discuss its significance later. A fault associated with the NE–SW trend of the Vang River passes through Salve and Tamine and is roughly parallel to the Patan fault and separated from it by the ≥ 1000 m high ridge. The point C on Figures 9 and 10 lies near Tamine, suggesting that the fault (?) passing through Tamine also dips to the northwest.

2B.6 Fractures in the Warna Area

In order to discover the geologic features which could possibly be associated with the seismicity near Warna Reservoir, the available geologic literature was reviewed. Detailed and reconnaissance geologic mapping in the Warna Reservoir area was carried out by the GEOLOGICAL SURVEY of INDIA (GSI). Most of the reports deal with the mapping of various lava flows in the area. Fourteen flows were delineated and were found to be subhorizontal or with low gradients and there was an absence of vertical displacements. A large number of fractures had been identified on aerial photographs and REDDY and JERATH (1984) confirmed four major fractures by ground checks. All these fractures are along small *nalas* (streams), tributaries of Warna River. No evidence of displacement was found on any of the fractures.

In order to delineate the weak zones in the Warna Valley, PESHWA (1991) reviewed the available Remote Sensing data. His report is the most detailed review of the features found in Remote Sensing images, and documents their ground check. The area studied was the catchment area of the Warna River (Fig. 15).

He found there are two NE–SW trending fracture zones, one lying between Ambole and Aloti and the other along a line from Petlond towards Bhogiv. These trends appear to be younger than the NW–SE trend defining the course of the Warna River. The intersection of the two fracture systems seems to control the observed seismicity, and observations suggest the fractures themselves may be fault related.

The Warna events on the other hand appear to be associated with faults trending both NE–SW and NW–SE and are located near their intersection.

2C. Geological Observations

SAHASRABUDHE *et al.* (1971) carried out detailed geologic mapping in the Koyna area following the December 1967 earthquake. They delineated 8 flows in the Koyna River Valley in a 245-m thick column. They further noted that "... *the flows have a very gentle* (1° *to* 2°) *westerly dip and are traversed by N–S to E–W trending vertical joints and several N–S trending shear zones*". According to the authors no conspicuous faults were noticed in the river valley.

Interestingly, SNOW (1982) noted that "... *crossing Koyna Dam is a vertical zone 1 to 3 m wide that had to be excavated and back-filled with concrete. In the tailrace tunnel, three near-vertical, north–northeast to north–northwest zones pinch and swell, with maximum widths as great as 10 m. Lavas on opposite sides of that zone are offset 3 m. Thus, it is consistent to regard all steep, continuous fractures and zones that strike N15°W to N15°E strike as faults*".

Thus, field mapping does suggest the possible presence of steeply dipping faults.

2D. Geophysical Studies

A variety of geophysical studies have been carried out in the Koyna-Warna area. These include deep seismic sounding on two east-west lines, detailed gravity surveys in a narrow strip just south of the Koyna Dam and aeromagnetic surveys over a broad area from the west coast of India and covering the study area.

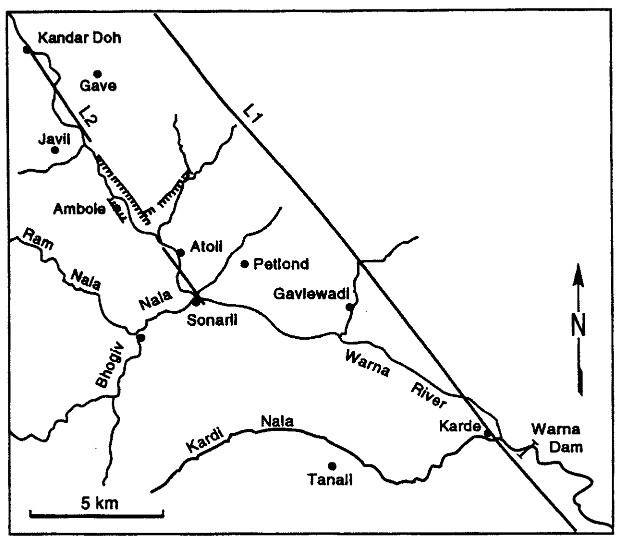

Figure 15
Locations of fractures and escarpments and streams (before impoundment) in the Warna Valley. LANDSAT lineament L_2 lies along the course of Warna River NW of Sonarli. Lineament L_1 lies to its NE.

2D.1 Deep Seismic Soundings

KAILA *et al.* (1981) described the results of Deep Seismic Soundings (DSS) on a 220-km long E–W profile from Guhagar on the west coast, passing through Koyna and east to Chorochi. The results revealed a number of reflection horizons below the Deccan Traps down to the Moho discontinuity. They found that below the Deccan Traps, the crustal section along this profile is cut into two blocks by a eastward dipping deep fault west of Koyna. The eastern block is further cut by another deep fault which affects only the deeper horizons including the Moho. They suggested that the Koyna earthquakes were due to movements on the faults east of Koyna.

2D.1.1 Reinterpretation of the Velocity Model

The multi-layer interpretation of the DSS data yielded a 14 layer model (Table 2) (KAILA, 1983). Reinterpretation of the DSS data along two east-west profiles using synthetic seismogram modeling revealed the presence of two low velocity zones (KRISHNA *et al.*, 1989). These two low velocity zones were found to occur in the upper crust and in the lower crust. On the Koyna II profile (located 60–70 km to the north and parallel to the Koyna I profile through Koyna) the velocity reduction occurs at a 6.0-km depth and there is a 3-km thick transition zone from 8.5 km to 11.5 km depth. The upper crustal low velocity zone was found to be one km deeper in the Koyna I profile. The second low velocity zone occurred at a depth of 26.0 km in the two profiles.

Interestingly the depth of most of the well located earthquakes (Fig. 8) lie in the low velocity zone interpreted by KRISHNA *et al.* (1989).

2D.2 Detailed Gravity Profiles

KAILASAM and MURTHY (1971) observed gravity along five short ($\sim$400 m) profiles across the Koyna River, south of the Koyna Dam, before the big bend near Helwak. The data suggested a possible shear zone (fault?) in a N–S direction parallel to the river course and to its west. The authors further suggested that the inferred fault from gravity data "*... is a buried one within the trap and extends deeper into the sub-trap formations and possibly into the basement rocks*".

2D.3 Aeromagnetic Data

In an effort to determine the thickness of the Deccan Trap rocks in the Koyna area, aeromagnetic data were acquired on 13 short profiles, each about 100 km long and spaced at 4 km (NEGI *et al.*, 1983). Data were recorded at elevations of 1220, 1524 and 2134 m, above mean sea level. The flight elevation 1220 m AMSL is only about 200–600 m about the ground surface and the flight lines were spaced 4 km apart. This led to the appearance of several high frequency (pseudo) anomalies (Fig. 6 in NEGI *et al.*, 1983). The pseudo-anomalies are absent in the residual anomaly map for the flight at 2134 m AMSL (Fig. 8 in NEGI *et al.*, 1983). Two

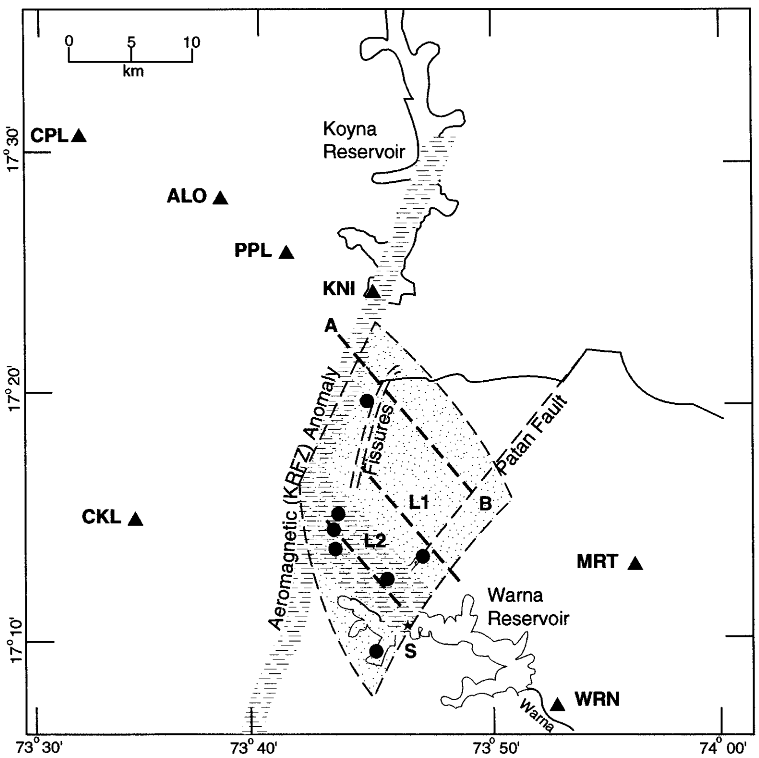

Figure 16
Interpreted structural boundaries from the aeromagnetic data. The inferred seismotectonic features are shown. The Koyna-River-Fault-Zone (KRFZ) is based on the pattern of aeromagnetic anomalies. The NW–SE pattern of aeromagnetic anomalies includes a portion of the Warna River and lies along lineament L_2. Other NW–SE block boundaries are indicated by lineaments L_1 and L_2 and line AB. The better located seismicity (1993–95) is roughly located within a seismogenic zone (stippled pattern) enclosed by the KRFZ to the west and Patan fault to the east (and a parallel fault to its southeast). The larger events in 1993–95 are shown by solid dots. The zone of fissures associated with the 1967 earthquake lies to the east of KRFZ.

major features were interpreted from the aeromagnetic maps (Fig. 16). The first a broad NNE–SSW zone, extends from north of the Koyna Dam, 40 km to its SSW. This feature abuts against a strong NW–SE anomaly along the upper reaches of the Warna River. This NW–SE anomaly is coincident with the lineament L_2 in Figure 15.

Thus the aeromagnetic data support the two major trends (NNE–SSW) along the (N–S) portion of the Koyna River and inferred as the main fault from various data discussed and the NW–SE trend of the Warna River upstream of Sonarli (Fig. 16).

This paper is concentrated towards Koyna as most of the data and studies pertain to the Koyna area. We realize that most of the current seismicity is in the Warna area. It is the Warna area that now bears careful watching and study.

3. Seismotectonics of the Koyna-Warna Area

In this section we combine various geological, geophysical, geomorphic data with seismicity data to delineate and describe the geometry of seismogenic structures. The results of this exercise show that the Koyna-Warna area is criss-crossed with several steeply-dipping fractures and faults. Some of these faults extend to great depths (>10 km). The geophysical and seismicity data also suggest the presence of a fluid-filled fracture zone where most of the larger events occur.

3A. A Fluid-filled Fracture Zone

Due to poor control on various parameters needed to accurately locate hypocenters, earlier estimates of the depth of seismicity in the Koyna-Warna region ranged from near surface to over 40 km. Those estimates were wrong. By carefully analyzing the hypocenters for accuracy in their depth estimates, we found that most of the seismicity is shallower than 15 km. Further, we found that most of the seismicity occurs between about 7 and 13 km depth. The detailed and careful inversion of deep sounding seismic data by KRISHNA *et al.* (1989) demonstrated that there is a low-velocity zone between the depths of about 6 and 13 km. A low velocity zone in the upper crust can be due to hotter rocks in which case we would expect plastic deformation and few earthquakes, or it could be due to fluid-filled fractured rocks. The observation that the low velocity zone is coincident with seismicity is interpreted to mean that it is associated with fluid-filled fractures. (There is abundant literature which demonstrates that fluid-filled fractures occur in mid-crust and are associated with a decrease in their seismic velocities see e.g., GAJEWSKI and PRODEHL 1987; WENZEL and SANDMEIER, 1992).

Consequently our first conclusion is that in the Koyna Warna area there is a fluid-filled upper crustal layer associated with a low velocity zone and most of the larger events occur in it.

3B. Koyna-River Fault Zone

In this section we present our interpretation of the 40–50 km long N10–15°E–S10–15°W trending Koyna-River fault zone (KRFZ).

AUDEN (1954), SAHASRABUDHE *et al.* (1971) and PATWARDHAN *et al.* (1995) among others have suggested that many subvertical fractures/faults encountered widely in the basalt flows in the Deccan Traps are related to throughgoing fractures in the underlying crystalline rocks. Movements on these faults in the crystalline basement control the geomorphic features in the overlying basalt e.g., the course of rivers, escarpments, cliffs, etc. Hence by studying the geomorphic features it is possible to infer subsurface faults underlying the basalt layers.

Evidence for the existence of the KRFZ comes from many sources. A study of aerial photographs (DESHPANDE and JAGTAP, 1971) revealed the presence of a predominance of N–S trending fractures. Surficial evidence of N–S faulting comes from a study of ancient geomorphic surfaces (terraces). SNOW (1982) demonstrated that they indicate faulting along the N–S stretch of the Koyna River with the west side downthrown. Evidence of shallow faulting was also obtained from the short E–W detailed gravity and magnetic profiles running just south of the Koyna Dam and crossing the Koyna River (KAILASAM and MURTY, 1971). They indicated a shallow N–S fault parallel and to the west of the Koyna River. The lateral extent of this fault is between the Koyna Dam and the right angle turn to the east in the Koyna River. Both the aeromagnetic data (NEGI *et al.*, 1983) and seismic refraction data (KAILA *et al.*, 1981) show that on a E–W profile through Koyna, the basalt is thicker under Koyna than under Alore to its west. The aeromagnetic data also show that there is a N–S to N10°E–S10°W trending fault along the Koyna River that extends at least 40 km to the south. Major aeromagnetic anomalies abut and terminate against this trend.

The 1967 main shock has also been interpreted to have occurred along the KRFZ. Various fault plane solutions (Fig. 11) suggest left-lateral strike-slip fault on a N10°E–S10°W steeply dipping fault. The seismicity data also support the KRFZ. The $M \geq 3.0$ earthquakes in 1992 define a N10°E–S10°W trend (Fig. 4), that is parallel and to the east of the magnetic anomaly defining the KRFZ. The ground fissures that were associated with the December 1967 earthquake are parallel and 1–2 km to the east of the magnetic anomaly and the 1992, $M \geq 3.0$ epicenters (Fig. 16). A 3-D stereo view from SSW of the best located earthquakes and lying on the postulated KRFZ reveals that the KRFZ defines a zone of activity, about 3–4 km wide and lying between depths of ~ 8 and 14 km. As most of these earthquakes are deeper than ~ 8 km and the ground fissures are parallel and ~ 1–2 km to the east, the inferred dip of the fault is 70–80° to the northwest, in general agreement with the focal mechanism solutions.

Another intriguing observation is that the surface projection of the KRFZ seems to lie between two wells that showed opposite coseismic response to the December 1967 earthquake. The water level in the well at Donichiwada rose whereas it went down in the well at Baje (Fig. 14). The response of the public to the 1967 main shock was also varied. Villages lying in a broad NNE-SSW zone parallel to the fault, but extending to large distances on either side, all reported sensing the ground motion in a N–S or NE–SW direction. This motion is consistent with what would be expected for a left-lateral strike-slip fault.

All these observations confirm the conclusions based on the fault plane solutions and seismicity that the 1967 Koyna earthquake occurred on a N10°E–S10°W fault and was associated with left-lateral strike-slip motion. The newer seismicity data also show that along the KRFZ the seismicity is generally deeper than about 6–7 km. We also note the KRFZ forms a western boundary of the seismicity (Fig.

16). We interpret this observation to mean that the KRFZ is the fractured edge of a crustal block. The regression relation between surface rupture length and magnitude (WELLS and COPPERSMITH, 1994) is log $SRL = 3.22 + 0.69$ M where SRL is the surface rupture length and M is Moment magnitude. For $M = 6.3$, the surface rupture length is 13.4 km. This length is consistent with the observed extent of ground fissures.

3C. Patan Fault

A NE–SW trending fault was postulated by PATWARDHAN *et al.* (1995), based on anomalous trends in the Koyna and Morna rivers near Patan (Fig. 14). If we extend this fault to its SW it lies along fault and escarpments near Ambole on the Warna River mapped by PESHWA (1991) and seen on LANDSAT data. We name this fault, the Patan fault.

The aftershocks of the *M* 5.4 earthquake on February 1, 1994 were well located and those in the first twenty-four hours occupy an area of ~250 sq km (Fig. 9). The epicenters of these aftershocks delineate a sharp SE boundary which is to the NW and parallel to the Patan fault. Some of the aftershocks and the main event (February 1, 1994 shock) were associated with normal faulting on a 45°NW dipping fault plane. If we project this fault plane to the surface (B on Figs. 9 and 10), it coincides with the Patan fault as described on the surface from geomorphic data. The absence of any aftershocks to the SE of the surface projection of the Patan fault suggest that it acts as a dipping boundary of a block.

Fault plane solutions of some events near Sonarli on the Warna River are also associated with normal faulting on NE–SW trending faults. PATWARDHAN *et al.* (1995) also suggested the presence of another NE–SW trending fault to the SE of the Patan fault. This fault passes through Salve and Tamine (Fig. 14). Interestingly this fault and the Patan fault lies to the SE and NW of a sharp, elongate NE–SW trending ridge with elevation exceeding 1000 m. We do not know the dip of the southern fault and speculate that it too dips to the NW, as is suggested by the deeper earthquakes in Figure 10.

3D. NW Trending Boundary Faults

A variety of data suggest the presence of steep NW trending faults that lie between the Koyna and Warna rivers and divide the area into distinct blocks.

The aftershocks of the February 1, 1994 earthquakes define one such block boundary (Fig. 9). A 3-D stereo view of this feature along NW–SE indicates that the earthquakes define a sharp NW–SE zone ~1–2 km wide and 10 km long extending from near surface to ~8 km depth (see also Fig. 10).

Another edge of a NW–SE trending block is defined by the aftershocks lying to the SW and parallel to the first set. This second set of aftershocks (Fig. 9) lies along a major NW–SE lineament seen on the LANDSAT and INSAT images (L1 in Figs. 14 and 15).

There were at least 5 aftershocks with $M \geq 4.0$ of the December 1967 M 6.3 event (Fig. 2). Although we could not obtain very accurate locations of these events, they are probably good to 2–3 km. These $M \geq 4.0$ events define a broad NW–SE zone. On Figure 9, AB shows the NW–SE trend of aftershocks of the February 1, 1994 earthquake. Note how the aftershocks of the 1967 main shock also lie along AB. This observation suggests that both the 1967 aftershocks and the February 1, 1994 aftershocks occurred along the same NW–SE fracture zone defining the NE edge of a tectonic block.

Langston and Franco-Spera (1985) obtained a fault plane solution of the aftershock on 12-12-67. It had a NW-SE strike and was associated with normal faulting. Composite fault plane solutions of several events lying in a NW–SE direction by Rastogi and Talwani (1980) also yielded normal faulting on NW–SE striking planes.

The Warna River upstream of Sonarli (Fig. 16) is also parallel to the NW trends described above and lies between a well developed NW–SE anomaly on the aeromagnetic map. Interestingly the NW trend and the seismicity continues only up to the KRFZ and does not extend beyond it. The seismicity along this stretch of the Warna River extends from near surface to $\sim$10–12 km depth.

The seismicity that followed the impoundment of Warna Dam (after 1992) also shows epicentral growth along this trend. Faults along this trend were also inferred by Peshwa (1991) on LANDSAT data and by field checking.

Thus various geological and seismicity data delineate several NW–SE trending faults.

3E. E–W Trending Faults

The right angle turn in the Koyna River near Helwak has been noted by many workers and interpreted to suggest the presence of an E–W fault. Further support for this view comes from the mapping of two prominent E–W aeromagnetic anomalies (see Fig. 8 in Negi *et al.* (1983)). On the E–W trend of the Koyna River (after the bend near Helwak) we note a broad 8–10 km long aeromagnetic high to the north of the river and a parallel low to its south. We interpret this observation to be a manifestation of an E–W fault.

The presence of topographic highlands ($>$1000 m) to the north and south of the river (Fig. 14) further suggests that the river has carved its path along the weak zone that faulting represents.

3F. Major Kinks and Intersections

Several authors have shown that intersections of faults or bends in the trends of faults serve as location for stress build-up (see e.g., KING and NABELEK, 1985; TALWANI, 1988; ANDREWS, 1989). We note a major concentration of seismicity near Sonarli on the Warna River. There the major NW–SE trend of the Warna River changes by 40° at the intersection with the Bhogiv *nala* (Figs. 5, 7, 14). This intersection of trends is the location of the most intense seismicity following the filling of the Warna Reservoir. The other major bend/intersection is near and to the south of the right angle bend in the Koyna River. This area has been the focus of intense past and ongoing seismicity.

4. Conclusions

Relocation of seismicity between 1963 and 1995 shows that it is widespread and extends from near the Koyna River to south and southwest of the Warna River. From an integration of an assortment of data with the seismicity pattern we conclude that the area lying between Koyna and Warna rivers can be divided into several seismogenic crustal blocks underlain by a fluid-filled fracture zone. This fluid-filled fracture zone lies at depths between ~6 and 13 km and is the location of most of the larger events ($M \geq 3.0$). The seismicity (as indicated by the better located earthquakes in 1993–95 and also the larger events) is bounded to the west by the Koyna River fault zone (KRFZ) (Fig. 16). KRFZ lies along the N–S portion of the Koyna River and extends S10°W for at least 40 km and dips steeply to the west. The current seismicity along the KRFZ lies at depths between ~6 and 14 km. We infer that the 1967 Koyna earthquake occurred along the KRFZ and was associated with a parallel set of ground fissures located 1–2 km to its east. The seismicity is bounded on the east by the NE–SW Patan fault (and possibly the parallel fault (?) through Tamine). This fault extends from Patan on the Koyna River SW to near Ambole on the Warna River. Patan fault dips ~45° to the NW possibly terminating in the KRFZ. The February 1994 M 5.4 occurred on the Patan fault at its intersection with KRFZ. The bounding KRFZ and Patan fault are intersected by several NW–SE fractures which extend from near surface to hypocentral depths. They form steep boundaries of the blocks and have surface manifestations. They are discernable on satellite images. These NW–SE fractures provide conduits for fluid pressure flow to hypocentral depths. Geomorphic and aeromagnetic data support the view that the E–W leg of the Koyna River is fault controlled. Sharp bends in the Koyna and Warna rivers (6 km S of Koyna Dam and near Sonarli, respectively) are locations of stress build-up and the observed seismicity.

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